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RESEARCH MEMORANDUM

EFFECT OF COMPRESSOR-OUTLET BLEEDOFF ON TURBOJET-ENGINE PERFORMANCE

By William A. Fleming, Lewis E. Wallner and John T. Wintler

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Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON
August 7, 1950

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EFFECT OF COMPRESSOR-OUTLET BLEEDOFF ON TURBOJET-ENGINE PERFORMANCE

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SUMMARY

In view of the possibility of utilizing the engine compressor to supply compressed air for jet-engine aircraft during flight, an investigation was conducted in the NACA Lewis altitude wind tunnel to determine the effect of compressor-outlet bleedoff on the performance of an axial-flow turbojet engine equipped with a variable-area exhaust nozzle. At a flight Mach number of 0.53, the engine was operated from 0.885 rated speed to rated speed at a pressure altitude of 25,000 feet and at 0.930 rated speed at a pressure altitude of 40,000 feet. At each condition the variable-area exhaust nozzle was locked in several positions and the bleedoff flow was varied from zero to approximately 0.10 of the engine air flow.

At a pressure altitude of 25,000 feet and a flight Mach number of 0.53, increasing the bleedoff flow from 0 to 0.10 of the engine air flow reduced the maximum net thrust obtainable with the standard exhaust-nozzle area to 0.775 of the initial thrust. This decrease in thrust was accompanied by a rise in specific fuel consumption to 1.177 of the initial value and required a reduction in engine speed from rated speed to 0.954 rated speed to prevent exceeding the turbine-outlet temperature limit. During operation at constant engine speed with a given exhaust-nozzle area, the net thrust and engine total-pressure ratio decreased and the specific fuel consumption and engine total-temperature ratio increased approximately linearly with the bleedoff flow. Improvements in performance offered during operation with a variable-area exhaust nozzle as compared to performance with a fixed-area nozzle were insignificant at the bleedoff and operating conditions investigated.

INTRODUCTION

Current aircraft often require compressed air during flight for such purposes as ice protection or cabin pressurization and conditioning. Because the quantity of air required varies considerably during a flight, any system that supplies sufficient air to satisfy the maximum demand will operate at a fraction of its total capacity during most of the flight. It is therefore doubly important that the supply system selected be of minimum weight and occupy a minimum of space. 1329

One method of supplying compressed air in jet-engine aircraft that is under investigation at the NACA Lewis laboratory consists in bleeding air from the compressor-outlet diffuser. This source of compressed air results in no weight or space penalty for the pumping equipment; however, compressor-outlet bleedoff will affect the engine performance. Use of compressor-outlet air might also require longer ducts than would be necessary for a separate source that allowed more flexibility in the choice of its location in the aircraft. An analytical method for calculating turbojet-engine performance with compressor-outlet bleedoff is presented in reference 1.

In order to evaluate further the effect of compressor-outlet bleedoff on engine performance, an experimental investigation was conducted in the altitude wind tunnel using an axial-flow turbojet engine equipped with a variable-area exhaust nozzle. The engine was operated at two altitudes, a single flight Mach number, and several engine speeds. At each engine speed the effect of varying the compressor-outlet bleedoff flow was determined for several exhaust-nozzle-outlet areas. Results presented herein indicate the effect of compressor-outlet bleedoff on engine performance for both fixed-area and variable-area exhaust-nozzle operation. Temperature and pressure losses through the bleedoff ducting system are also discussed.

INSTALLATION AND INSTRUMENTATION

An axial-flow turbojet engine was installed in the test section of the altitude wind tunnel. A variable-area exhaust nozzle installed on the engine permitted operation over a wide range of turbine-outlet temperatures at each engine speed and bleedoff-flow rate. Dry air was introduced to the engine through a duct from the tunnel make-up air system. This air was throttled from approximately sea-level pressure to the desired pressure at the engine inlet, while the tunnel pressure was maintained to correspond to the desired altitude. Refrigeration coils in the make-up air system permitted control of the inlet-air temperature.

The bleedoff system installed on the engine is illustrated in figure 1. Compressor-outlet air was supplied to a manifold through four extraction ports incorporated in the compressor-outlet diffuser for the purpose of air bleedoff. The air passed from the manifold into a cylindrical duct extending rearward along the top of the engine and was then discharged into the tunnel test section. A butterfly valve was installed at the outlet of the bleedoff duct to control the bleedoff flow. The system was designed for a velocity through the manifold of approximately 300 feet per second when bleeding off 0.10 of the air at rated engine speed. The cross-sectional areas of the lower and upper portions of the manifold were 0.250 and 0.885, respectively, of the duct cross-sectional area. No insulation was installed on any part of the bleedoff system.

Pressures and temperatures were measured at four stations in the engine: engine inlet, compressor outlet, turbine outlet, and tail pipe. A temperature and pressure survey was also installed 18 inches upstream of the butterfly valve in the bleedoff duct. Cross sections of each measuring station indicating the temperature and pressure surveys are shown in figure 2.

PROCEDURE

The investigation was conducted at pressure altitudes of 25,000 and 40,000 feet and at inlet pressures corresponding to a flight Mach number of 0.53. The inlet-air total temperature was maintained at approximately 30° F throughout the investigation. This temperature was selected because it represents the condition at which aircraft icing is most prevalent and therefore the condition at which the maximum flow might be required from the bleedoff system. At an altitude of 25,000 feet, the engine was operated at 0.885, 0.930, and 1.00 of rated speed, and at an altitude of 40,000 feet the engine was operated at 0.930 of rated speed. These flight conditions and engine speeds were selected to approximate possible cruising conditions of jet-engine aircraft.

At each flight condition and engine speed, performance data were obtained over a range of bleedoff flows with the variable-area exhaust nozzle locked in several positions. For each nozzle position, data were obtained along an operating line from a minimum limit of either a tail-pipe temperature of 1370° R or zero bleedoff flow to a maximum limit of either a tail-pipe temperature of 1665° R or a bleedoff-flow rate of 0.10 of the engine air flow.

Thrust and air flows were calculated from pressure and temperature measurements at the several measuring stations, and fuel flow was measured with a calibrated rotameter. The effective exhaust-nozzle-outlet areas were calculated from measurements of exhaust-gas temperature, pressure, and flow rate. An average of the calculated exhaust-nozzle areas for any one locked nozzle position was used as the effective area for that operating line. Methods of calculating the performance variables and the effective nozzle areas are given in the appendix.

RESULTS AND DISCUSSION

In order to maintain constant engine speed while air is bled from the compressor outlet of a turbojet engine having a fixed exhaust-nozzle area, the enthalpy drop per unit flow through the turbine must be increased approximately in proportion to the fraction of air bled from the compressor outlet. It is characteristic of axial-flow turbojet engines having a fixed exhaust-nozzle area that such a required increase in enthalpy drop per unit flow through the turbine will increase the turbine-inlet and turbine-outlet total temperatures and decrease the turbine-outlet total pressure. A typical set of data presented in figure 3 for 0.930 rated engine speed, an altitude of 25,000 feet, a flight Mach number of 0.53, and for several fixed-exhaust-nozzle areas indicates the trend of the tail-pipe total temperature, total pressure, net thrust, and specific fuel consumption with bleedoff flow. Exhaust-nozzle areas are given as fractions of a standard-nozzle area. This standard-nozzle area is defined as the effective area with which a tail-pipe total temperature of 1665° R, corresponding to an engine total-temperature ratio of 3.4, was obtained at rated engine speed, an altitude of 25,000 feet, and a flight Mach number of 0.53. The net thrust and the specific fuel consumption obtained at each altitude with this standard-nozzle area and a tail-pipe total temperature of 1665° R, are referred to as net thrust at limiting temperature and specific fuel consumption at limiting temperature.

The engine-inlet total temperature and pressure were approximately constant; therefore, these data show that as the bleedoff flow was increased for any fixed exhaust-nozzle area, the tail-pipe total temperature was appreciably increased and the turbine-outlet total pressure was slightly reduced. The reductions in exhaust-gas flow and turbine-outlet total pressure with increased bleedoff flow had a greater effect on net thrust than the increase in tail-pipe total temperature, and the net thrust was therefore reduced (fig. 3(c)). It should be noted that during operation, at

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this engine speed with zero bleedoff flow and the smallest nozzle area, the ratio of net thrust to the net thrust at limiting temperature was 1.0. The attainment of this thrust at 0.930 rated engine speed was possible because the slight decrease in air flow below the value at rated speed was accompanied by an improvement in compressor efficiency. The increased pressure and temperature energy removed from the engine as the bleedoff flow was increased resulted in a rise in specific fuel consumption (fig. 3(d)). With a given exhaust-nozzle area, the variations in the engine-performance parameters presented in figure 3 were nearly linear with bleedoff flow. Except for the specific fuel consumption, the slope of the curves for each parameter was approximately the same for all exhaust-nozzle areas. The increase in specific fuel consumption with bleedoff flow was more pronounced with the largest exhaust-nozzle areas than with the smaller areas. The performance trends shown for this operating condition were similar to those for the other conditions investigated. Complete data for each flight condition are presented in table I.

Effects of compressor-outlet bleedoff on the engine performance characteristics at altitudes of 25,000 and 40,000 feet are compared in figure 4. This increase in altitude from 25,000 to 40,000 feet with a constant engine speed, exhaust-nozzle area, flight Mach number, and engine-inlet temperature raised the engine total-pressure ratio, total-temperature ratio, and ratio of net thrust to net thrust at limiting temperature by approximately a fixed increment throughout the range of bleedoff flows investigated. There was no consistent effect of altitude on the ratio of specific fuel consumption to specific fuel consumption at limiting temperature. In explaining these trends, it should be pointed out that a reduction in compressor efficiency of approximately 0.04 accompanied this increase in altitude. Consequently, when operating with the standard-nozzle area, which gave limiting turbine-outlet temperature at rated speed and an altitude of 25,000 feet, limiting turbine-outlet temperature was obtained at approximately 0.98 rated engine speed at an altitude of 40,000 feet. The engine total-temperature ratio and engine total-pressure ratio at 0.93 rated speed were therefore higher at an altitude of 40,000 feet than at 25,000 feet. It also follows that the ratio of net thrust at 0.93 rated speed to net thrust at limiting temperature for an altitude of 40,000 feet was higher than the net-thrust ratio for an altitude of 25,000 feet. Although the specific fuel consumption was higher at an altitude of 40,000 feet than at 25,000 feet, there was no consistent effect of altitude on the ratio of specific fuel consumption to specific fuel consumption at limiting temperature, as might be expected.

The effect of compressor-outlet bleedoff on engine performance for operation with the standard-area nozzle at an altitude of 25,000 feet and a flight Mach number of 0.53 is shown in figure 5. Results are presented for operation at maximum thrust as limited by a tail-pipe temperature of 1665° R, and at 0.85 and 0.75 of the net thrust at limiting temperature. These results were obtained from cross plots of data for each engine speed similar to the data in figure 3. With a tail-pipe temperature of 1665° R, the maximum obtainable thrust decreased nearly linearly to 0.775 of the net thrust at limiting temperature as the bleedoff flow was increased from 0 to 0.10 of the engine air flow. Accompanying this decrease in thrust was an increase in specific fuel consumption to 1.177 of the specific fuel consumption at limiting temperature, and a reduction in engine speed to 0.954 of rated speed was required to maintain a constant tail-pipe temperature. During operation at constant thrust, the specific fuel consumption and the tail-pipe temperature increased as the bleedoff flow was raised, and an increase in engine speed was required to maintain constant thrust. Operation at 0.85 rated net thrust was limited by the tail-pipe temperature to a maximum bleedoff flow of 0.071 of the engine air flow. Variation of the performance with bleedoff flow calculated by the analytical method of reference 1 and using the characteristics of an axial-flow engine of different design was in favorable agreement with the experimental results.

A comparison of the performance obtained at the limiting tail-pipe temperature of 1665° R with the standard-area nozzle and a variable-area nozzle, which permitted operation at constant engine speed, is presented in figure 6. Performance with the variable-area nozzle is shown for both rated engine speed and 0.93 rated speed. The maximum net thrust with the variable-area nozzle was from 0 to 0.016 lower at rated engine speed and from 0 to 0.008 higher at 0.93 rated speed than with the standard-area nozzle. With the variable-area nozzle, the specific fuel consumption was from 0 to 0.045 higher at rated speed and 0.013 to 0.020 lower at 0.93 rated speed than with the standard-area nozzle. The slightly lower thrusts and higher specific fuel consumption obtained at rated speed than at 0.93 rated speed are associated with the negligible increase in air flow and the appreciable decrease in compressor efficiency accompanying an increase in engine speed from 0.93 rated speed to rated speed.

The variation of specific fuel consumption, tail-pipe temperature, engine speed, and exhaust-nozzle area with bleedoff at 0.75 of the net thrust obtainable at limiting temperature is shown in figure 7 for operation with the standard-area nozzle and with the

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variable-area nozzle at 0.93 rated speed, the engine speed at which the lowest specific fuel consumption was obtained at limiting temperature (fig. 6). The specific fuel consumption with the variable-area exhaust nozzle varied from 0.015 higher to 0.010 lower than that with the standard-area nozzle as the bleedoff flow was increased from 0 to 0.10 of the engine air flow. Throughout this range of bleedoff flows, the tail-pipe temperature differed by less than 10° F between the two methods of operation. An examination of all the data obtained shows that improvements in performance by use of a variable-area exhaust nozzle as compared to a fixed-area nozzle were insignificant.

The performance data presented thus far have indicated the effect of compressor-outlet bleedoff on performance at specific operating conditions. Engine performance obtained with bleedoff at all operating conditions investigated can be summarized by the engine pumping characteristics, as shown in figure 8. These data, which are cross-plotted from data such as those presented in figures 3(a) and 3(b), show the variation of engine total-pressure ratio with engine total-temperature ratio for several bleedoff flows, with lines of constant exhaust-nozzle area superimposed. Such curves are useful for selecting data at any bleedoff condition for the flight conditions and engine speeds investigated to determine the effect of bleedoff on the performance.

Increasing the bleedoff flow at a given operating condition and exhaust-nozzle area shifted the operating point in the direction of increased engine total-temperature ratios and reduced engine total-pressure ratios, as indicated in figure 3. The trends of the pumping characteristics are in close agreement with those analytically determined by the method of reference 1 for an axial-flow engine of different design, except that between bleedoff flows of 0 and 0.03 of the engine air flow, changes in engine total-temperature ratio with a constant exhaust-nozzle area were considerably greater than those analytically determined. A study of the data has shown that the relation between engine total-temperature ratio and engine total-pressure ratio is very sensitive to small changes in exhaust-nozzle area. A change in effective exhaust-nozzle area of approximately 1 percent, which is within the accuracy of the calculated effective area, would account for the difference in trends between the experimental and analytical results.

An increase in altitude from 25,000 to 40,000 feet shifted the pumping characteristics in such a manner that, at a given bleedoff flow, exhaust-nozzle area, and engine speed, the engine total-temperature ratio was substantially increased with only a slight change in engine total-pressure ratio. Increasing engine speed with a given exhaust-nozzle area and bleedoff flow so shifted the pumping characteristics that both the engine total-temperature ratio and engine total-pressure ratio were raised considerably.

The variation of the conditions at the compressor outlet and the bleedoff measuring station with bleedoff flow during operation at maximum thrust is shown in figure 9. As the bleedoff flow was raised from 0 to 0.10 of the engine air flow, with the attendant decrease in engine speed, the velocity in the bleedoff duct increased to 290 feet per second and the compressor-outlet total pressure, static pressure, and total temperature were reduced. Because the bleedoff flow was extracted from the compressor-outlet diffuser through flush openings in the diffuser wall, the compressor-outlet static pressure represents the maximum total pressure obtainable in the bleedoff duct. The total pressure in the duct with no bleedoff flow was equal to the compressor-outlet static pressure; however, as the flow was increased to 0.10 of the engine air flow, with the accompanying rise in bleedoff-flow velocity, the bleedoff total pressure dropped 0.6 of an atmosphere below the compressor-outlet static pressure. Temperature loss through the uninsulated duct between the compressor outlet and the bleedoff measuring station amounted to as much as 75° F at a bleedoff-flow rate of 0.02 of the engine air flow. As the bleedoff flow and consequently the velocity were raised, this temperature loss decreased rapidly and was only 5° F at 0.10 of the engine air flow. Bleedoff total temperatures at flow rates below 0.02 of the engine air flow are not shown because insufficient data were obtained to establish the trend of the curve between this flow and the no-flow condition.

SUMMARY OF RESULTS

Results of an experimental investigation to determine the effect of compressor-outlet bleedoff on engine performance are summarized as follows:

1. For engine operation with the standard exhaust-nozzle area at an altitude of 25,000 feet and a flight Mach number of 0.53, increasing the bleedoff flow from 0 to 0.10 of the engine air flow reduced the maximum net thrust, as limited by tail-pipe temperature, to 0.775 of the initial thrust, increased the specific

fuel consumption to 1.177 of the initial value, and required a speed reduction from rated engine speed to 0.954 of rated speed to prevent exceeding the tail-pipe temperature limit.

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2. Improvements in performance with bleedoff by use of a variable-area exhaust nozzle as compared to performance with a fixed-area nozzle were insignificant at the conditions investigated.

3. During operation at constant engine speed with a fixed exhaust-nozzle area, an increase in bleedoff flow reduced the net thrust and engine total-pressure ratio and increased the specific fuel consumption and engine total-temperature ratio. These variations were approximately linear with bleedoff flow.

4. Increasing the altitude during operation with a given bleedoff flow, exhaust-nozzle area, and engine speed substantially increased the engine total-temperature ratio with only a slight change in engine total-pressure ratio. An increase in engine speed with a given exhaust-nozzle area and bleedoff flow substantially raised both engine total-temperature and total-pressure ratios.

5. During operation at maximum thrust with the standard exhaust-nozzle area, an increase in bleedoff flow from 0 to 0.10 of the engine air flow, with the attendant decrease in engine speed, lowered the compressor-outlet total pressure, static pressure, and total temperature, and lowered the total pressure in the bleedoff duct from 0 to 0.6 atmosphere below the compressor-outlet static pressure. The total-temperature loss from the compressor outlet to the bleedoff duct was reduced from 75° to 5° F as the bleedoff flow was raised from 0.02 to 0.10 of the engine air flow.

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APPENDIX - CALCULATIONS

Symbols

The following symbols are used in this report:

A area, sq ft

a speed of sound, ft/sec

F_n net thrust, lb

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g acceleration due to gravity, 32.17 ft/sec^2

P total pressure, lb/sq ft

p static pressure, lb/sq ft

R gas constant, 53.4 ft-lb/(lb)($^{\circ}$F)

T total temperature, $^{\circ}$R

V velocity, ft/sec

W weight flow, lb/sec

γ ratio of specific heat at constant pressure to specific heat at constant volume

ρ density, lb/cu ft

Subscripts:

0 free-stream ambient

1 engine inlet

2 compressor outlet

4 turbine outlet

5 tail pipe

a engine air

b bleedoff survey station

c compressor-seal leakage air

f fuel

g exhaust gas

j station at which jet reaches free-stream static pressure

n exhaust nozzle

Methods of Calculation

Engine air flow. - The air flow into the compressor was obtained from measurements at the engine inlet (station 1) and was calculated by the following equation:

$$W_{a,1} = p_1 A_1 \sqrt{\frac{2\gamma g}{(\gamma-1)RT_1}\left(\frac{P_1}{p_1}\right)^{\frac{\gamma-1}{\gamma}}\left[\left(\frac{P_1}{p_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]} \tag{1}$$

Bleedoff flow. - The maximum velocity at the measuring station in the bleedoff duct was 290 feet per second; therefore, the flow was calculated by the incompressible-flow equation

$$W_b = A_b \sqrt{2\rho_b (P_b - p_b) g} \tag{2}$$

Use of this equation rather than the compressible-flow equation introduced a maximum error of less than 0.5 percent of the flow measurement.

Net thrust. - Net thrust was calculated assuming no total-pressure loss through the tail pipe and complete expansion of the exhaust gases to ambient pressure by the following relation:

$$F_n = \frac{W_g}{g} V_j - \frac{W_{a,1}}{g} V_0 \tag{3}$$

where, assuming complete free-stream total-pressure recovery,

$$V_0 = \sqrt{\frac{2\gamma}{(\gamma-1)} gRT_1 \left[1 - \left(\frac{p_0}{P_1}\right)^{\frac{\gamma-1}{\gamma}}\right]} \tag{4}$$

and

$$V_j = \sqrt{\frac{2\gamma_j}{(\gamma_j-1)}\, gRT_5 \left[1 - \left(\frac{p_0}{P_4}\right)^{\frac{\gamma_j-1}{\gamma_j}}\right]} \tag{5}$$

Because a more accurate turbine-outlet temperature measurement was obtained at station 5 than at station 4, T_5 was used in equation (5). The gas flow was calculated from

$$W_g = W_{a,1} - W_b - W_c + W_f \tag{6}$$

Compressor-seal leakage air W_c was measured by pressure and temperature instrumentation in the leakage line.

Exhaust-nozzle area. - The effective exhaust-nozzle-outlet area was calculated assuming ambient pressure at the nozzle outlet when the jet was subsonic and critical pressure ratio at the nozzle outlet when the jet was supersonic. When P_4/p_0 was less than the critical pressure ratio, the nozzle area was determined from the relation

$$A_n = \frac{W_g}{\rho_j V_j} = \frac{W_g R T_5}{p_0 V_j}\left(\frac{p_0}{P_4}\right)^{\frac{\gamma-1}{\gamma}} \tag{7}$$

When P_4/p_0 exceeded the critical pressure ratio, the nozzle area was calculated from the equation

$$A_n = \frac{W_g}{\rho_n V_n} \tag{8}$$

Because

$$V_n = a_n = \sqrt{\left(\frac{2}{\gamma_n+1}\right) gRT_5}$$

and

$$p_n = P_4 \left(\frac{2}{\gamma_n+1}\right)^{\frac{\gamma_n}{\gamma_n-1}}$$

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then

$$A_n = \frac{W_g R T_5}{P_4 a_n} \left(\frac{\gamma_n+1}{2}\right)^{\frac{1}{\gamma_n-1}} \tag{9}$$

REFERENCE

1. Hensley, Reece V., Rom, Frank E., and Koutz, Stanley L.: Effect of Heat and Power Extraction on Turbojet-Engine Performance. I - Analytical Method of Performance Evaluation with Compressor-Outlet Air Bleed. NACA TN 2053, 1950.

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TABLE I - PERFORMANCE WITH COMPRESSOR-OUTLET BLEEDOFF

Run	Altitude (ft)	Flight Mach number	Ratio of engine speed to rated engine speed	Ratio of bleedoff flow to engine air flow, $W_b/W_{a,1}$	Tunnel static pressure, p_0 (lb/sq ft)	Engine-inlet total pressure, P_1 (lb/sq ft)	Engine-inlet total temperature, T_1 (°R)	Ratio of net thrust to net thrust at limiting temperature	Ratio of specific fuel consumption to consumption at limiting temperature	Ratio of exhaust-nozzle area to standard nozzle area	Average ratio of exhaust-nozzle area to standard nozzle area	Engine total-pressure ratio, P_4/P_1	Tail-pipe total temperature, T_5 (°R)	Engine total-temperature ratio, T_5/T_1	Bleedoff velocity, V_b (ft/sec)	Ratio of compressor-outlet total pressure to ambient pressure, P_2/p_0	Ratio of compressor-outlet static pressure to ambient pressure, p_2/p_0	Compressor-outlet total temperature, T_2 (°R)	Ratio of total pressure at bleedoff station to ambient pressure, P_b/p_0	Bleedoff station total temperature, T_b (°R)
1	25,000	0.522	0.885	0	781	939	486	0.986	0.979	0.906	0.906	1.95	1680	3.46	0	5.81	5.62	826	5.62	758
2		.535		0	781	949	491	.926	.972	.933	.929	1.85	1598	3.26	0	5.72	5.52	826	5.52	758
3		.541		.026	781	952	491	.896	1.008	.923	.929	1.83	1618	3.30	56	5.66	5.44	820	5.43	788
4		.535		.041	781	949	494	.879	1.049	.926	.929	1.82	1656	3.35	93	5.58	5.38	822	5.29	805
5		.543		.052	781	954	494	.871	1.069	.930	.929	1.80	1685	3.41	120	5.51	5.32	816	5.16	806
6		.533		0	781	947	491	.880	.961	.943	.943	1.80	1542	3.14	0	5.61	5.42	821	5.42	756
7		.534		.030	781	948	492	.842	1.013	.944	.943	1.76	1570	3.19	68	5.53	5.32	818	5.29	791
8		.538		0	779	949	491	.866	.959	.951	.946	1.78	1527	3.11	0	5.63	5.43	820	5.42	754
9		.533		.026	781	947	489	.823	1.013	.943	.946	1.75	1541	3.15	60	5.52	5.32	813	5.30	779
10		.531		.048	781	946	490	.809	1.038	.945	.946	1.73	1576	3.22	111	5.42	5.22	810	5.10	795
11		.529		.072	781	944	493	.788	1.088	.946	.946	1.72	1625	3.30	178	5.33	5.14	808	4.83	801
12		.542		0	781	953	485	.828	.952	.968	.951	1.72	1460	3.01	0	5.57	5.37	807	5.38	742
13		.534		.046	781	948	483	.788	1.023	.938	.951	1.72	1502	3.11	103	5.48	5.27	797	5.18	775
14		.535		.071	781	949	485	.766	1.085	.952	.951	1.69	1562	3.22	174	5.36	5.17	797	4.86	789
15		.530		.103	781	945	475	.766	1.164	.946	.951	1.70	1614	3.40	276	5.36	5.16	781	4.50	775
16		.530		.042	781	945	489	.662	1.044	.987	.991	1.56	1383	2.83	99	5.20	4.99	801	4.92	783
17		.522		.071	781	939	487	.647	1.104	.981	.991	1.55	1438	2.95	183	5.09	4.90	799	4.60	791
18		.529		.108	781	944	491	.627	1.206	.973	.991	1.54	1499	3.05	316	5.04	4.85	794	4.13	790
19		.530		.108	781	945	493	.517	1.270	1.009	1.009	1.41	1377	2.79	326	4.86	4.67	789	3.97	785
20	25,000	0.534	0.930	0	781	948	492	1.004	0.989	0.945	0.945	1.92	1666	3.39	0	6.02	5.81	850	5.82	763
21		.534		0	781	948	489	.965	.987	.959	.953	1.86	1614	3.30	0	5.99	5.77	844	5.78	761
22		.535		.020	781	949	491	.944	1.011	.956	.953	1.85	1635	3.33	43	5.90	5.68	841	5.66	797
23		.534		.051	781	948	488	.906	1.057	.945	.953	1.83	1669	3.42	118	5.75	5.53	831	5.38	814
24		.534		0	781	948	491	.944	.983	.960	.957	1.84	1591	3.24	0	5.93	5.71	842	5.72	759
25		.535		.028	781	949	490	.909	1.022	.950	.957	1.82	1607	3.28	62	5.85	5.61	837	5.58	794
26		.535		.036	781	949	488	.904	1.037	.960	.957	1.81	1628	3.34	80	5.79	5.57	832	5.49	806
27		.530		.077	781	945	487	.854	1.116	.953	.957	1.77	1678	3.45	191	5.62	5.42	822	5.03	813
28		.535		0	781	949	491	.875	.983	.986	.976	1.77	1531	3.12	0	5.81	5.59	838	5.61	754
29		.531		.035	781	946	490	.859	1.025	.981	.976	1.75	1580	3.22	81	5.66	5.44	834	5.38	805
30		.535		.053	781	949	491	.837	1.061	.975	.976	1.73	1600	3.26	125	5.62	5.40	825	5.23	809
31		.533		.084	781	947	490	.812	1.122	.969	.976	1.72	1655	3.36	219	5.53	5.33	822	4.86	816
32		.533		.104	781	947	492	.778	1.181	.969	.976	1.69	1679	3.41	294	5.46	5.26	822	4.55	817
33		.535		0	781	949	490	.857	.958	.997	.989	1.72	1493	3.05	0	5.74	5.52	834	5.54	757
34		.534		.037	781	948	490	.823	1.022	.979	.989	1.71	1538	3.14	85	5.62	5.40	827	5.32	800
35		.533		.077	781	947	490	.784	1.107	.989	.989	1.67	1605	3.28	198	5.49	5.28	822	4.89	814
36		.534		.102	781	948	490	.757	1.167	.992	.989	1.65	1638	3.34	294	5.39	5.20	817	4.49	813
37		.533		0	781	947	491	.791	.967	1.014	1.007	1.65	1426	2.90	0	5.63	5.40	831	5.42	753
38		.535		.030	781	949	493	.797	.975	1.004	1.007	1.63	1459	2.96	68	5.56	5.33	829	5.30	795
39		.535		.057	781	949	492	.742	1.067	1.007	1.007	1.61	1502	3.05	140	5.46	5.24	822	5.05	809
40		.534		.090	781	948	492	.705	1.149	1.003	1.007	1.59	1550	3.15	246	5.36	5.15	819	4.63	812
41		.532		.103	781	946	491	.712	1.167	.991	1.007	1.61	1706	3.21	299	5.33	5.13	817	4.42	812
42		.531		0	781	946	492	.726	.995	1.039	1.022	1.58	1372	2.79	0	5.56	5.34	828	5.35	733
43		.536		.029	781	950	491	.712	1.030	1.020	1.022	1.58	1397	2.84	68	5.48	5.26	823	5.22	788
44		.533		.059	781	947	490	.687	1.090	1.019	1.022	1.56	1440	2.94	147	5.37	5.16	816	4.95	804
45		.533		.085	781	947	490	.664	1.157	1.016	1.022	1.54	1480	3.02	230	5.28	5.08	813	4.62	806
46		.535		.102	781	949	492	.655	1.183	1.014	1.022	1.53	1515	3.08	296	5.38	5.04	813	4.38	809
47		.534		0	781	948	489	.661	.987	1.073	1.057	1.50	1299	2.66	0	5.42	5.19	822	5.21	747
48		.534		.039	781	948	491	.629	1.069	1.057	1.057	1.48	1344	2.74	95	5.30	5.08	815	4.99	794
49		.531		.071	781	946	492	.604	1.143	1.052	1.057	1.46	1380	2.80	186	5.21	5.01	813	4.70	803
50		.535		.101	781	949	489	.587	1.225	1.047	1.057	1.45	1432	2.93	297	5.13	4.93	808	4.27	804
51		.535		.053	781	949	492	.588	1.097	1.063	1.058	1.44	1321	2.68	135	5.22	5.01	814	4.85	798
52		.533		.104	781	947	493	.546	1.254	1.052	1.058	1.41	1388	2.81	311	5.07	4.86	807	4.18	801
53		.531		.102	781	946	492	.506	1.257	1.088	1.088	1.36	1338	2.72	313	5.00	4.79	804	4.13	799

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TABLE I - PERFORMANCE WITH COMPRESSOR-OUTLET BLEEDOFF - Concluded

Run	Altitude (ft)	Flight Mach number	Ratio of engine speed to rated engine speed	Ratio of bleedoff flow to engine air flow, $W_b/W_{a,1}$	Tunnel static pressure, p_0 (lb/sq ft)	Engine-inlet total pressure, P_1 (lb/sq ft)	Engine-inlet total temperature, T_1 (°R)	Ratio of net thrust to net thrust at limiting temperature	Ratio of specific fuel consumption to consumption at limiting temperature	Ratio of exhaust-nozzle area to standard nozzle area	Average ratio of exhaust-nozzle area to standard nozzle area	Engine total-pressure ratio, P_4/P_1	Turbine-outlet total temperature, T_5 (°R)	Engine total-temperature ratio, T_5/T_1	Bleedoff velocity, V_b (ft/sec)	Ratio of compressor-outlet total pressure to ambient pressure, P_2/p_0	Ratio of compressor-outlet static pressure to ambient pressure, p_2/p_0	Compressor-outlet total temperature, T_2 (°R)	Ratio of total pressure at bleedoff station to ambient pressure, P_b/p_0	Bleedoff station total temperature, T_b (°R)
54	25,000	0.538	1.000	0	781	951	486	1.032	1.009	0.999	0.999	1.88	1685	3.47	0	6.29	6.07	873	6.08	724
55		.536		0	781	950	487	1.002	.998	1.013	1.000	1.84	1657	3.40	0	6.21	5.98	874	5.99	775
56		.538		.020	781	951	490	.989	1.014	.994	1.000	1.81	1672	3.41	42	6.14	5.92	875	5.91	805
57		.535		.032	781	949	489	.951	1.059	1.000	1.000	1.81	1691	3.46	71	6.06	5.82	871	5.78	832
58		.535		.053	781	949	489	.917	1.104	.994	1.000	1.79	1713	3.50	127	5.96	5.72	865	5.56	845
59		.534		0	781	948	487	.930	1.037	1.014	1.009	1.80	1625	3.34	0	6.12	5.89	871	5.91	773
60		.535		.043	781	949	491	.909	1.078	1.007	1.009	1.77	1678	3.42	100	5.94	5.71	868	5.61	841
61		.535		.055	781	949	487	.899	1.107	1.006	1.009	1.76	1695	3.48	132	5.92	5.69	859	5.52	839
62		.539		0	781	952	490	.933	1.002	1.026	1.019	1.76	1584	3.23	0	——	——	——	——	783
63		.536		.027	781	950	489	.896	1.052	1.021	1.019	1.74	1608	3.29	60	5.98	5.75	866	5.73	817
64		.534		.041	781	948	490	.890	1.077	1.023	1.019	1.73	1639	3.34	96	5.90	5.67	865	5.58	835
65		.534		.063	781	949	487	.865	1.125	1.006	1.019	1.73	1663	3.41	160	5.85	5.62	857	5.40	840
66		.539		.072	781	951	488	.862	1.142	1.020	1.019	1.71	1696	3.47	188	5.82	5.59	859	5.29	846
67		.538		0	781	951	490	.895	1.014	1.044	1.030	1.71	1552	3.17	0	6.02	5.79	871	5.80	764
68		.535		.028	781	949	490	.872	1.052	1.024	1.030	1.70	1571	3.21	62	5.94	5.71	865	5.68	817
69		.535		.057	781	949	488	.833	1.112	1.024	1.030	1.68	1605	3.29	136	5.80	5.57	857	5.41	835
70		.535		.074	781	949	485	.820	1.148	1.029	1.030	1.67	1644	3.39	192	5.72	5.50	853	5.17	843
71		.538		.082	781	951	491	.801	1.181	1.028	1.030	1.65	1665	3.39	217	5.71	5.50	856	5.07	847
72		.534		.100	781	948	491	.788	1.224	1.031	1.030	1.64	1698	3.46	283	5.66	5.46	853	4.77	844
73		.536		0	781	950	485	.828	.998	1.075	1.054	1.63	1468	3.03	0	5.90	5.67	859	5.68	754
74		.534		.045	781	948	488	.772	1.106	1.048	1.054	1.60	1521	3.12	107	5.74	5.50	855	5.40	826
75		.533		.067	781	947	486	.763	1.240	1.056	1.054	1.59	1556	3.20	168	5.67	5.44	849	5.20	830
76		.534		.086	781	948	488	.742	1.197	1.041	1.054	1.58	1596	3.27	234	5.60	5.39	849	4.90	838
77		.536		.106	781	950	484	.740	1.237	1.051	1.054	1.58	1642	3.39	314	5.58	5.36	843	4.57	834
78		.535		0	781	949	488	.727	1.034	1.104	1.086	1.52	1389	2.85	0	5.75	5.51	857	5.51	760
79		.540		.056	774	944	487	.681	1.133	1.078	1.086	1.50	1432	2.94	136	5.65	5.39	847	5.27	819
80		.541		.086	774	945	486	.654	1.222	1.084	1.086	1.49	1490	3.07	238	5.52	5.32	841	4.84	830
81		.536		.111	781	950	489	.650	1.270	1.076	1.086	1.48	1550	3.17	345	5.43	5.22	842	4.39	834
82		.534		0	781	948	487	.687	1.045	1.126	1.110	1.48	1343	2.76	0	5.68	5.45	853	5.47	752
83		.536		.064	781	950	486	.638	1.168	1.103	1.110	1.45	1402	2.88	165	5.49	5.25	841	5.08	821
84		.534		.104	781	948	486	.609	1.293	1.102	1.110	1.44	1490	3.07	319	5.36	5.17	838	4.39	831
85		.534		.104	781	948	486	.506	1.412	1.174	1.174	1.32	1395	2.87	321	5.24	5.03	832	4.30	823
86	40,000	0.535	0.930	0	391	475	487	1.002	0.988	0.986	0.978	1.80	1609	3.30	0	5.87	5.66	845	5.67	743
87		.527		.024	391	472	489	.961	1.038	.973	.978	1.78	1635	3.34	50	5.76	5.54	842	5.51	773
88		.527		.056	391	472	490	.927	1.095	.976	.978	1.76	1680	3.43	127	5.64	5.44	837	5.26	803
89		.535		0	391	475	486	.957	.987	.981	.980	1.76	1565	3.22	0	5.82	5.62	840	5.61	728
90		.522		.033	391	470	489	.931	1.036	.976	.980	1.75	1603	3.28	71	5.45	5.48	839	5.44	779
91		.530		.043	391	473	487	.923	1.049	.977	.980	1.74	1610	3.31	95	5.67	5.46	834	5.36	790
92		.530		.083	391	473	488	.874	1.141	.985	.980	1.70	1682	3.45	210	5.52	5.33	830	4.91	808
93		.525		0	391	471	486	.933	.995	1.010	.991	1.72	1537	3.16	0	5.78	5.58	844	5.58	735
94		.525		.036	391	471	486	.884	1.049	.993	.991	1.70	1558	3.21	79	5.64	5.42	836	5.36	778
95		.530		.049	391	473	485	.861	1.076	.983	.991	1.68	1568	3.23	109	5.60	5.39	834	5.26	791
96		.525		.068	391	471	490	.848	1.110	.983	.991	1.68	1604	3.27	163	5.52	5.32	831	5.07	803
97		.527		.079	391	472	486	.839	1.138	.986	.991	1.67	1617	3.33	198	5.46	5.28	824	4.90	802
98		.535		0	391	475	494	.865	1.056	1.004	.991	1.66	1486	3.01	0	5.76	5.46	844	5.47	752
99		.527		.097	391	472	494	.778	1.152	.979	.991	1.62	1625	3.29	267	5.32	5.12	830	4.51	813
100		.527		0	391	472	485	.824	.960	1.047	1.023	1.60	1428	2.94	0	5.57	5.36	834	5.36	749
101		.525		.039	391	471	486	.774	1.042	1.009	1.023	1.59	1455	3.00	89	5.44	5.23	830	5.16	782
102		.519		.072	391	469	486	.774	1.053	1.023	1.023	1.59	1501	3.10	179	5.36	5.16	825	4.90	800
103		.517		.097	391	468	486	.729	1.174	1.013	1.023	1.55	1560	3.22	267	5.27	5.08	821	4.45	803
104		.540		0	389	474	492	.754	.965	1.057	1.043	1.52	1382	2.81	0	5.49	5.27	836	5.28	761
105		.527		.056	391	472	492	.691	1.109	1.043	1.043	1.50	1440	2.93	136	5.39	5.13	852	4.96	799
106		.530		.092	391	473	493	.673	1.176	1.026	1.043	1.49	1500	3.04	255	5.18	4.99	826	4.45	808
107		.532		.096	391	474	492	.512	1.324	1.115	1.115	1.31	1368	2.78	281	4.98	4.79	818	4.20	803

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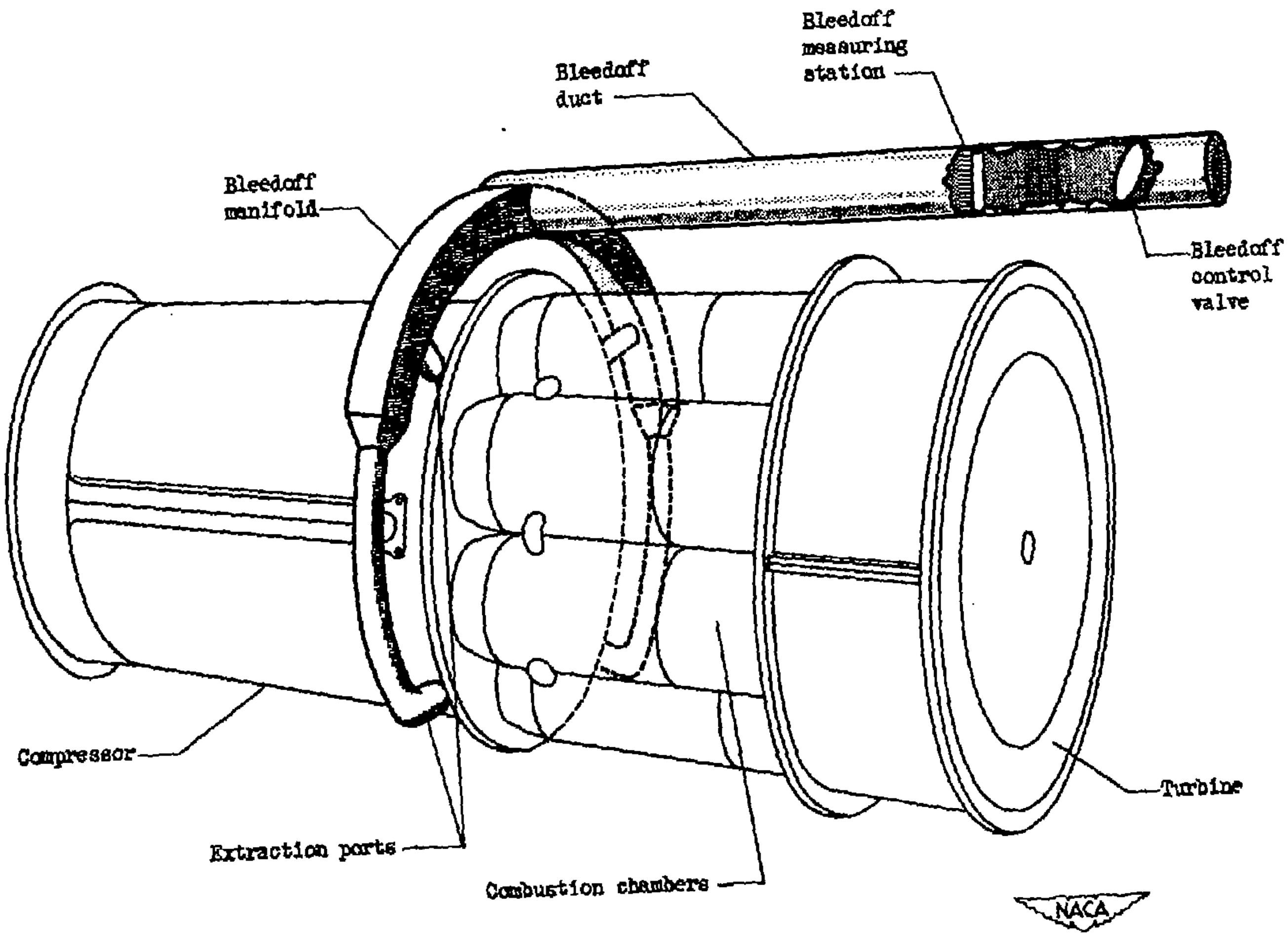

Figure 1. - Compressor-outlet bleedoff system installed on axial-flow turbojet engine.

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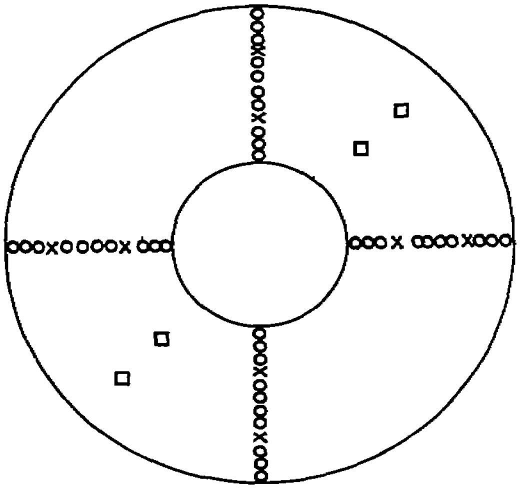
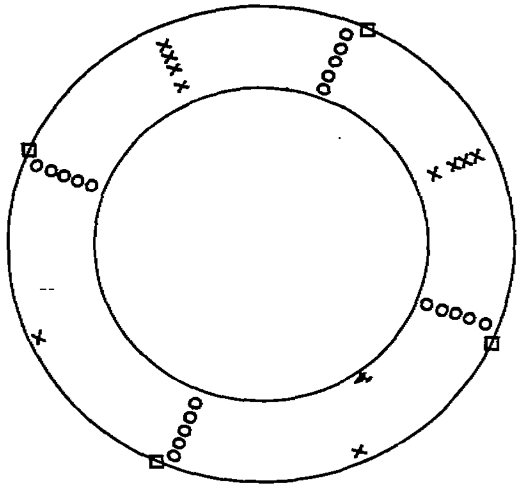
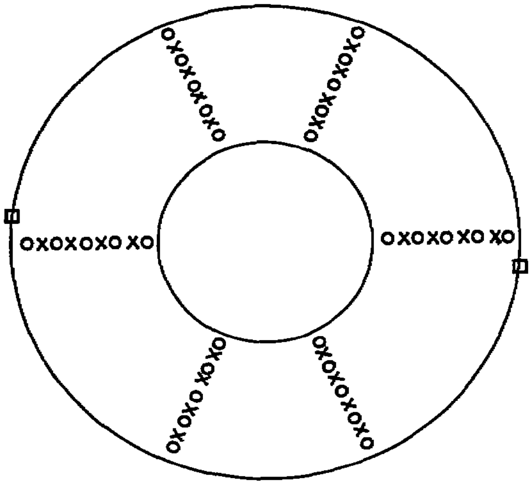


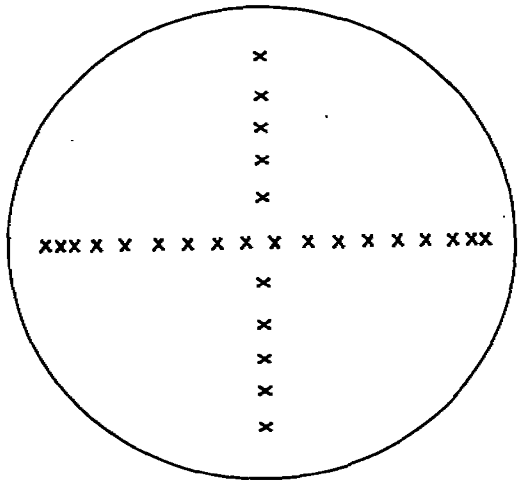
(a) Compressor inlet, station 1.



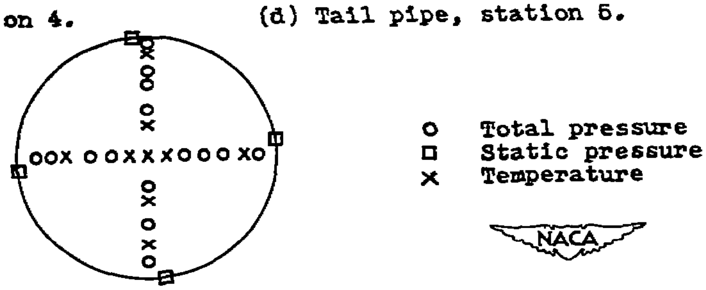
(b) Compressor outlet, station 2.



(c) Turbine outlet, station 4.

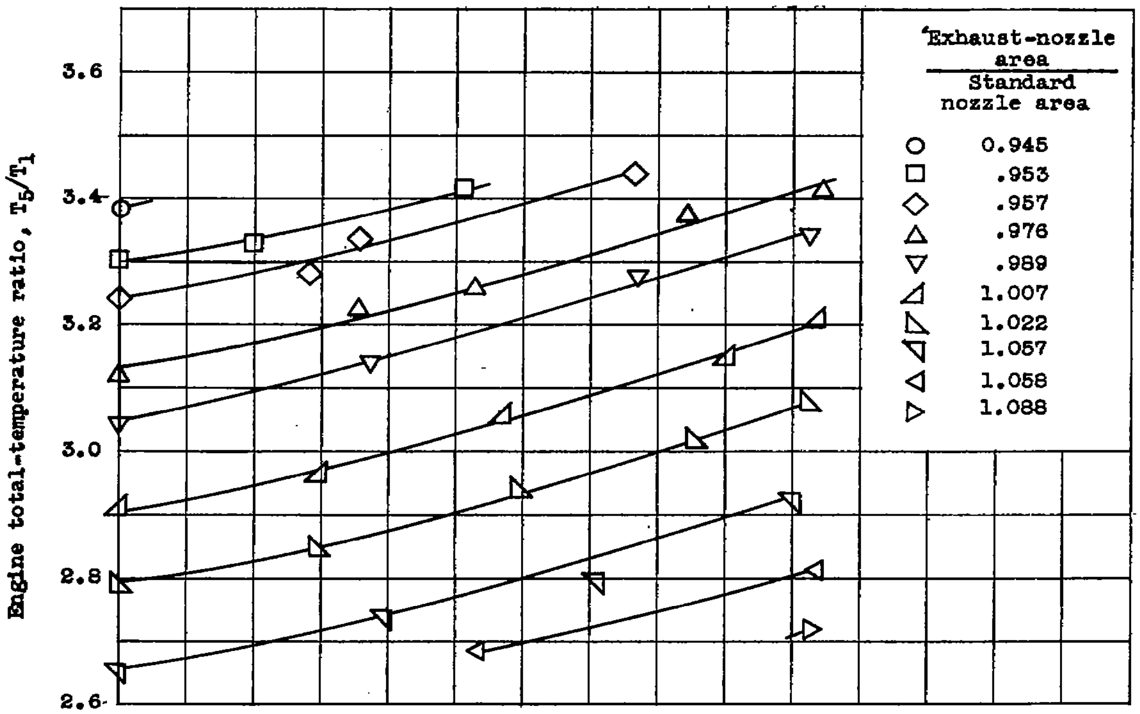


(d) Tail pipe, station 5.

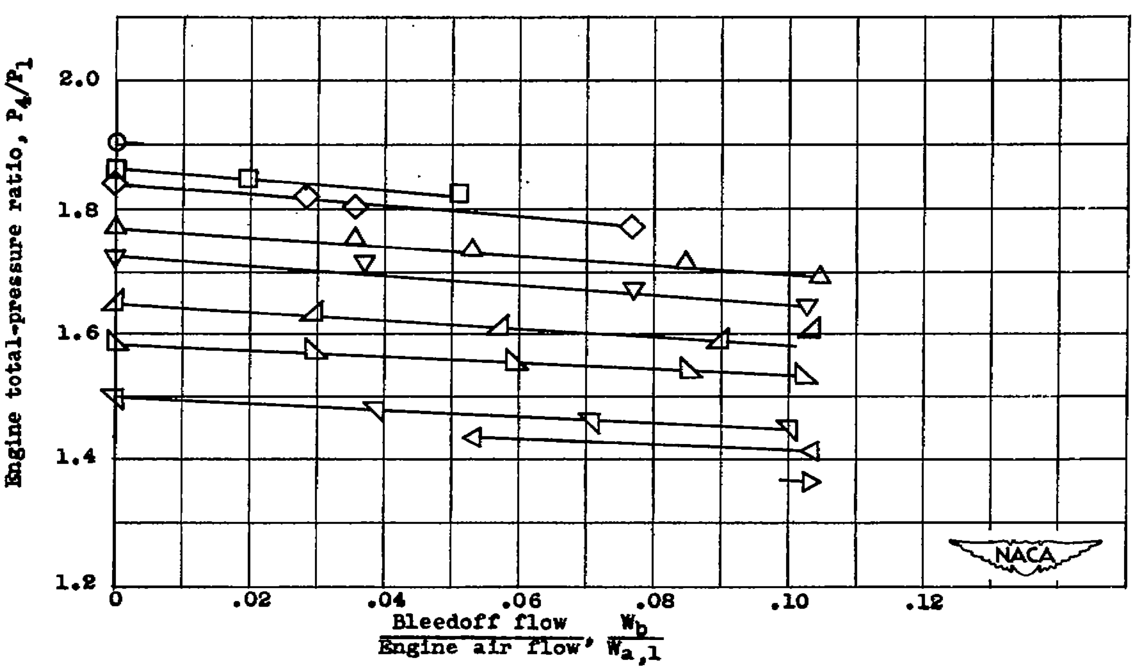


(e) Bleedoff measuring station.

Figure 2. - Temperature and pressure surveys installed at measuring stations in engine.



(a) Engine total-temperature ratio.



(b) Engine total-pressure ratio.

Figure 3. - Effect of compressor-outlet bleedoff on engine performance. Altitude, 25,000 feet; flight Mach number, 0.53; engine speed, 0.93 rated.

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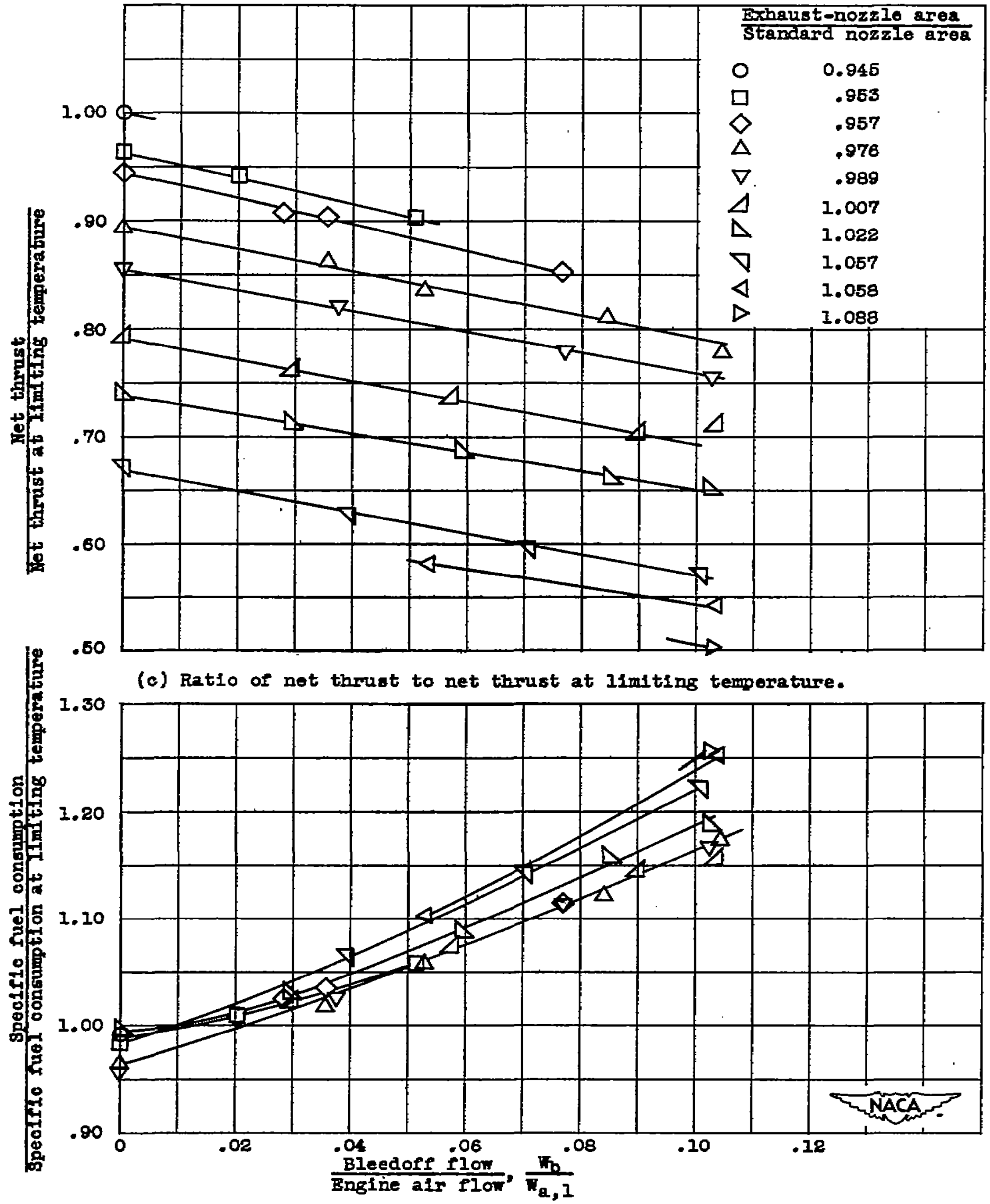
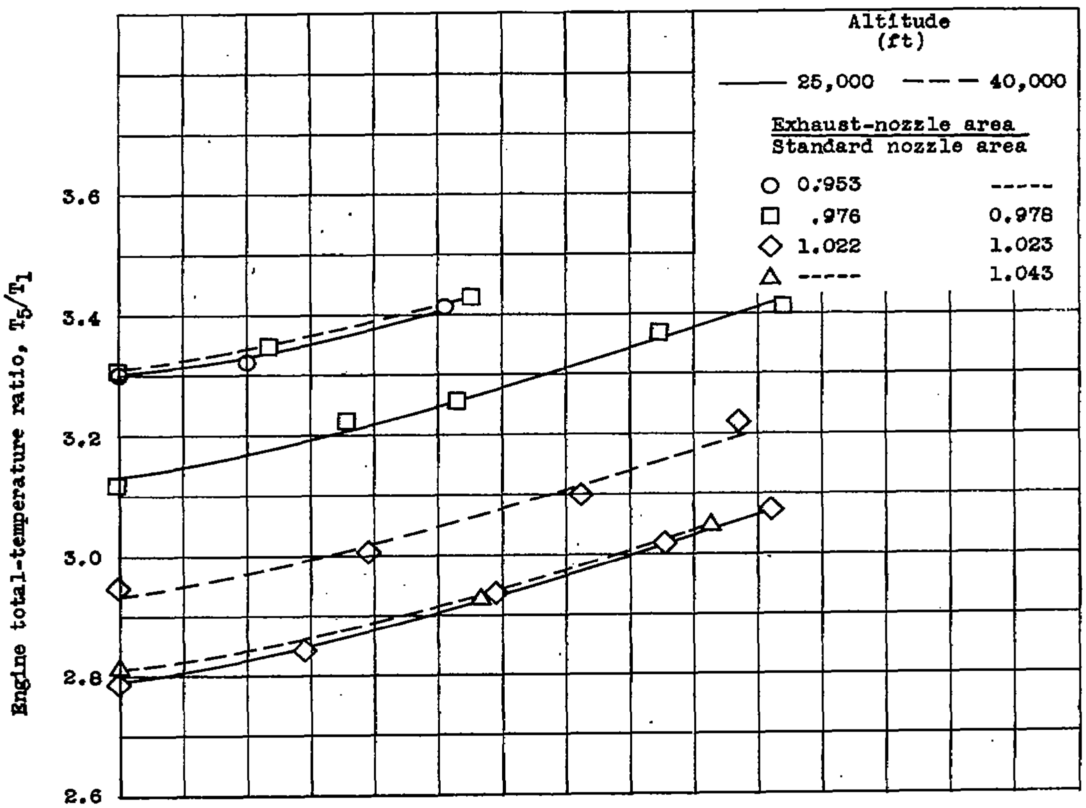


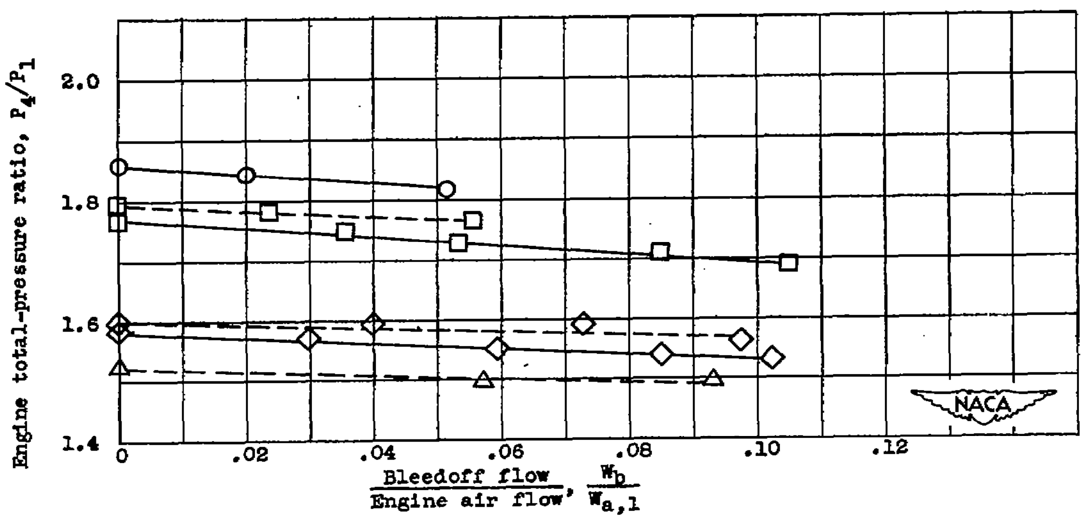
(c) Ratio of net thrust to net thrust at limiting temperature.

(d) Ratio of specific fuel consumption to specific fuel consumption at limiting temperature.

Figure 3. - Concluded. Effect of compressor-outlet bleedoff on engine performance. Altitude, 25,000 feet; flight Mach number, 0.53; engine speed, 0.93 rated.



(a) Engine total-temperature ratio.



(b) Engine total-pressure ratio.

Figure 4. - Effect of altitude on variation of engine performance with bleedoff flow. Engine speed, 0.93 rated; flight Mach number, 0.53.

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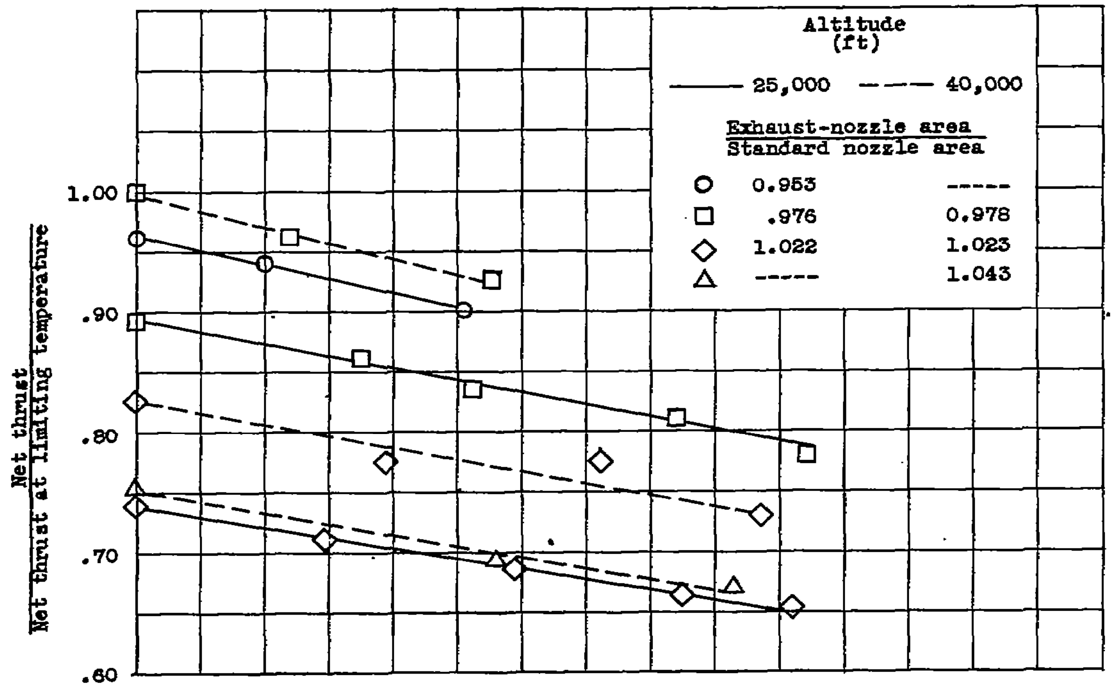
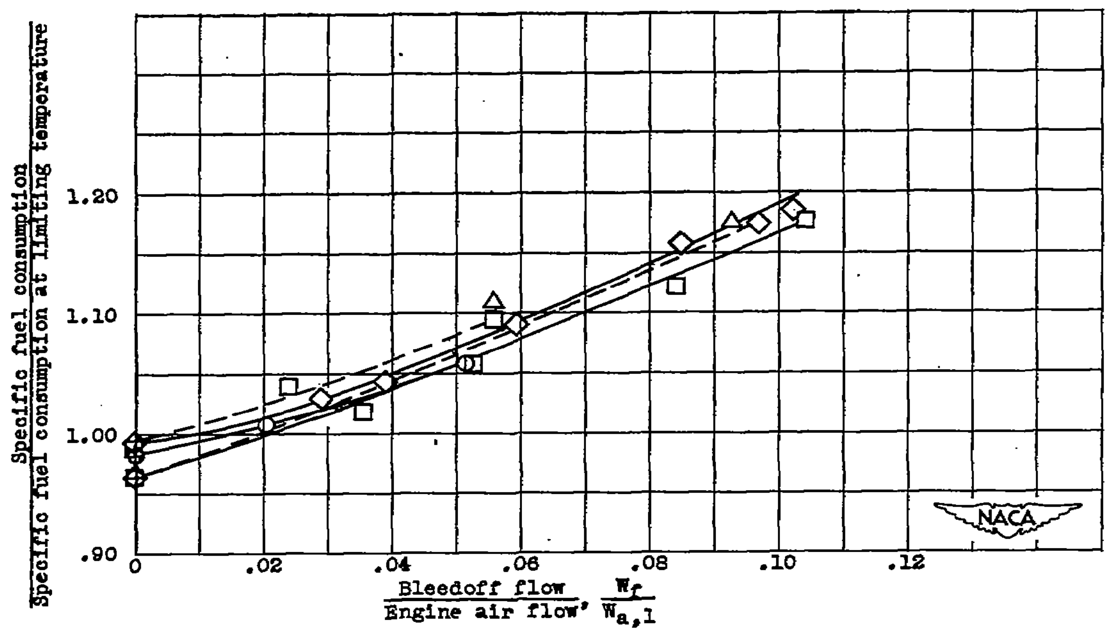
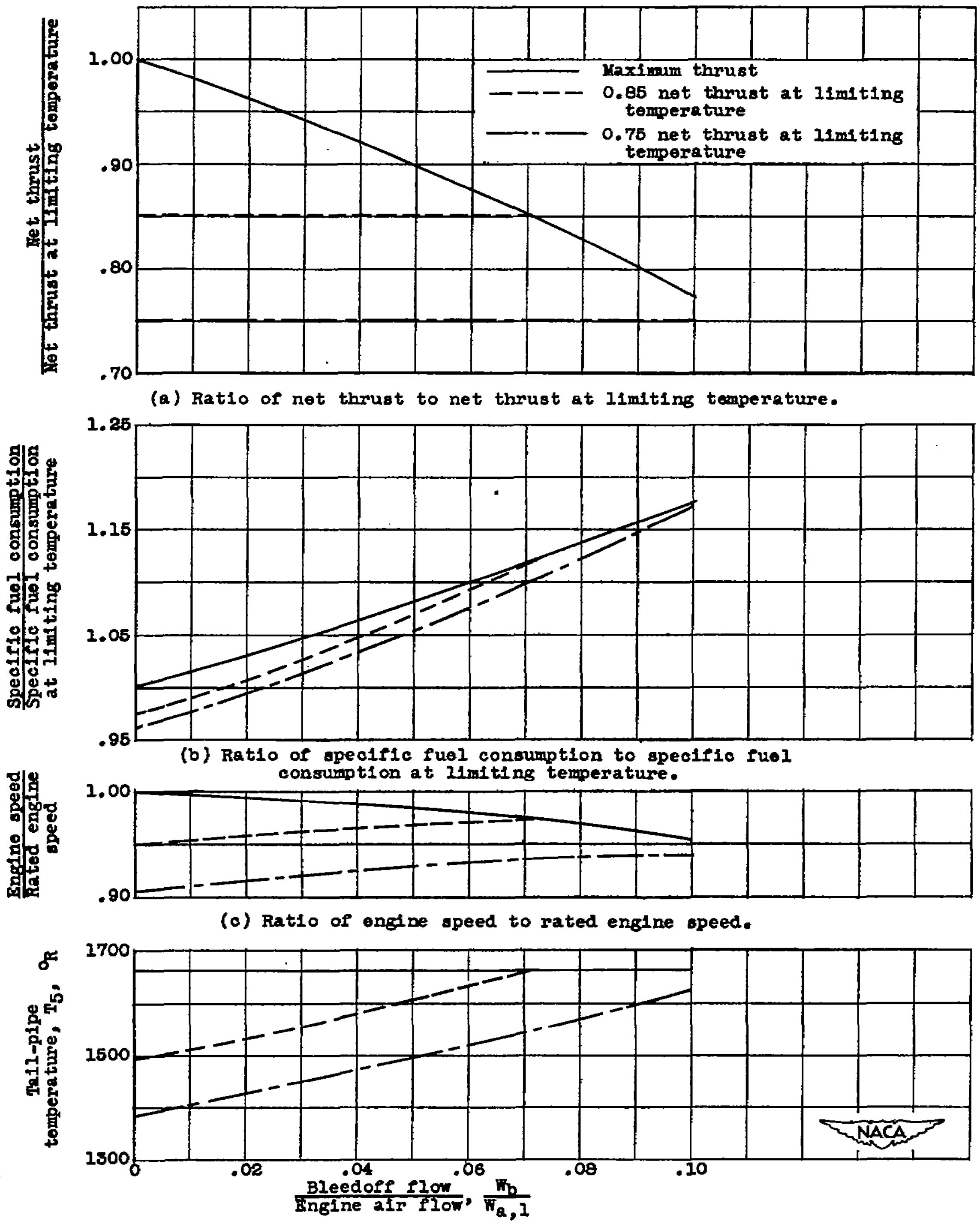


(c) Ratio of net thrust to net thrust at limiting temperature.



(d) Ratio of specific fuel consumption to specific fuel consumption at limiting temperature.

Figure 4. - Concluded. Effect of altitude on variation of engine performance with bleedoff flow. Engine speed, 0.93 rated; flight Mach number, 0.53.



(d) Tail-pipe temperature.

Figure 5. - Variation of engine performance with compressor-outlet bleedoff. Altitude, 25,000 feet; flight Mach number, 0.53; standard exhaust-nozzle area.

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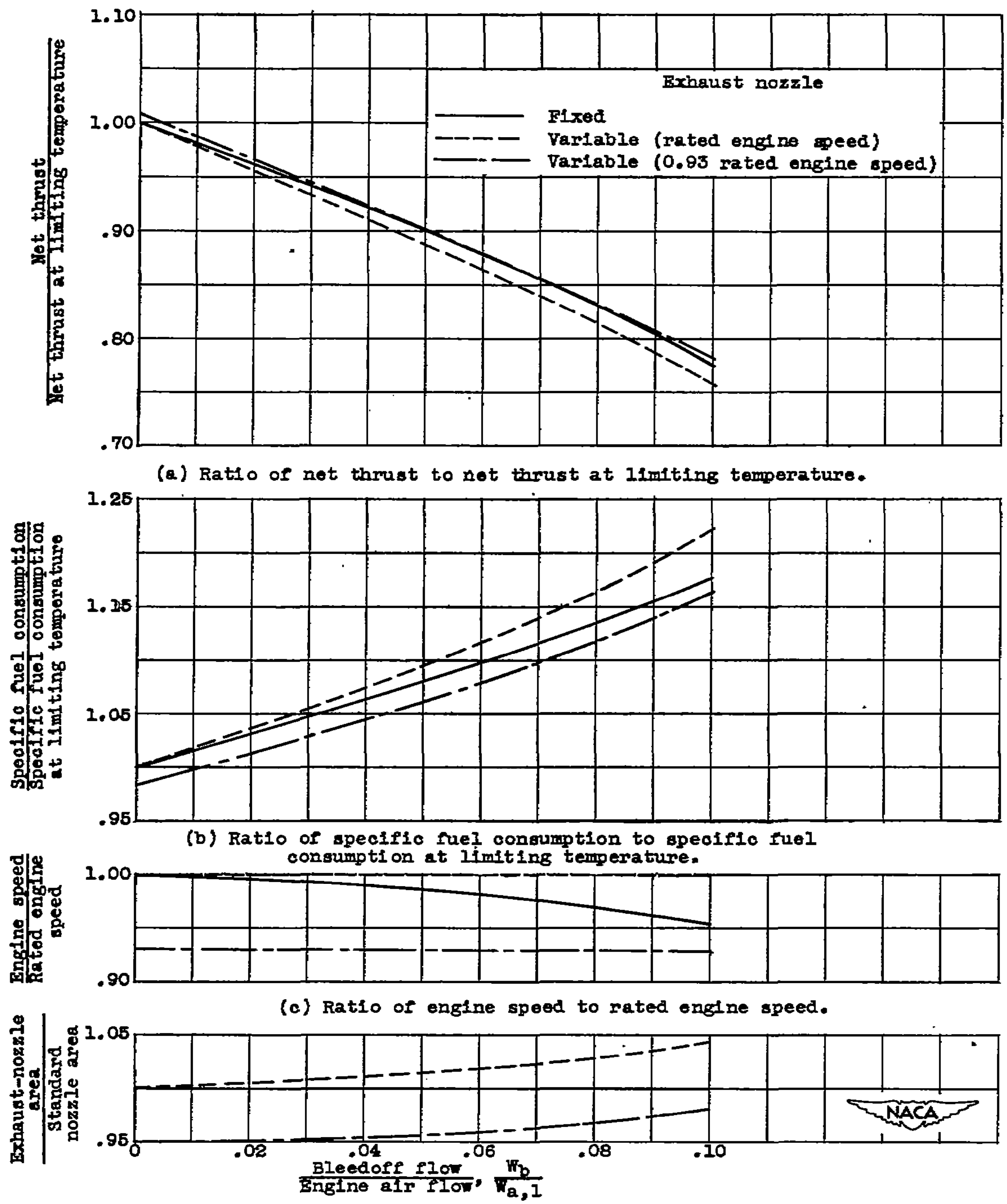

(a) Ratio of net thrust to net thrust at limiting temperature.

(b) Ratio of specific fuel consumption to specific fuel consumption at limiting temperature.

(c) Ratio of engine speed to rated engine speed.

(d) Ratio of exhaust-nozzle area to standard nozzle area.

Figure 6. - Comparison of engine performance variation with compressor-outlet bleedoff for operation with fixed- and variable-area exhaust nozzles at maximum net thrust. Altitude, 25,000 feet; flight Mach number, 0.53; tail-pipe temperature, 1665° R.

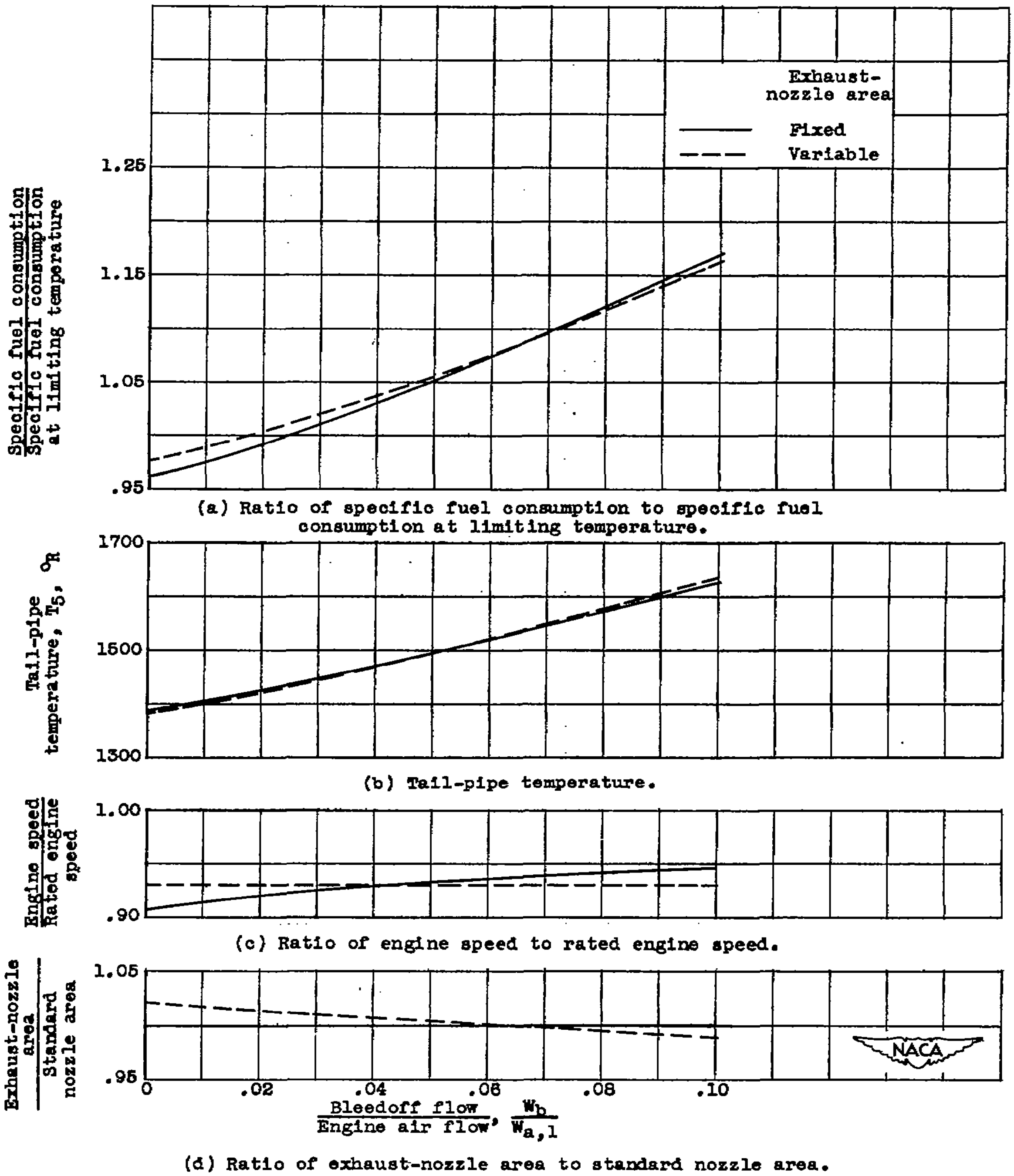

Figure 7. - Comparison of engine performance variation with compressor-outlet bleedoff for operation with fixed- and variable-area exhaust nozzles at 0.75 of net thrust obtainable at limiting temperature. Altitude, 25,000 feet; flight Mach number, 0.53.

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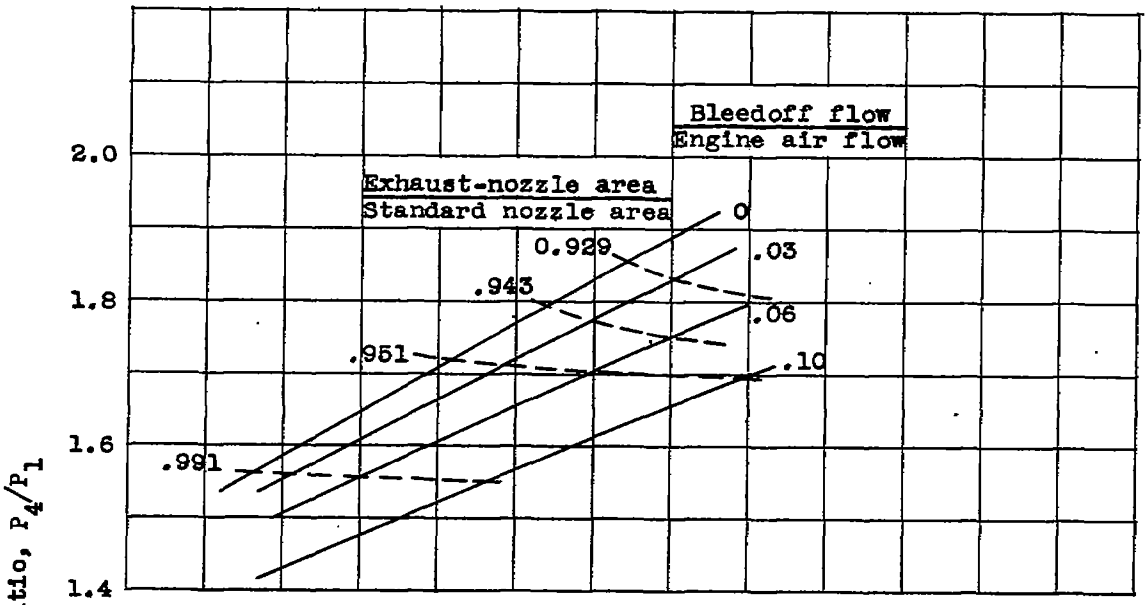
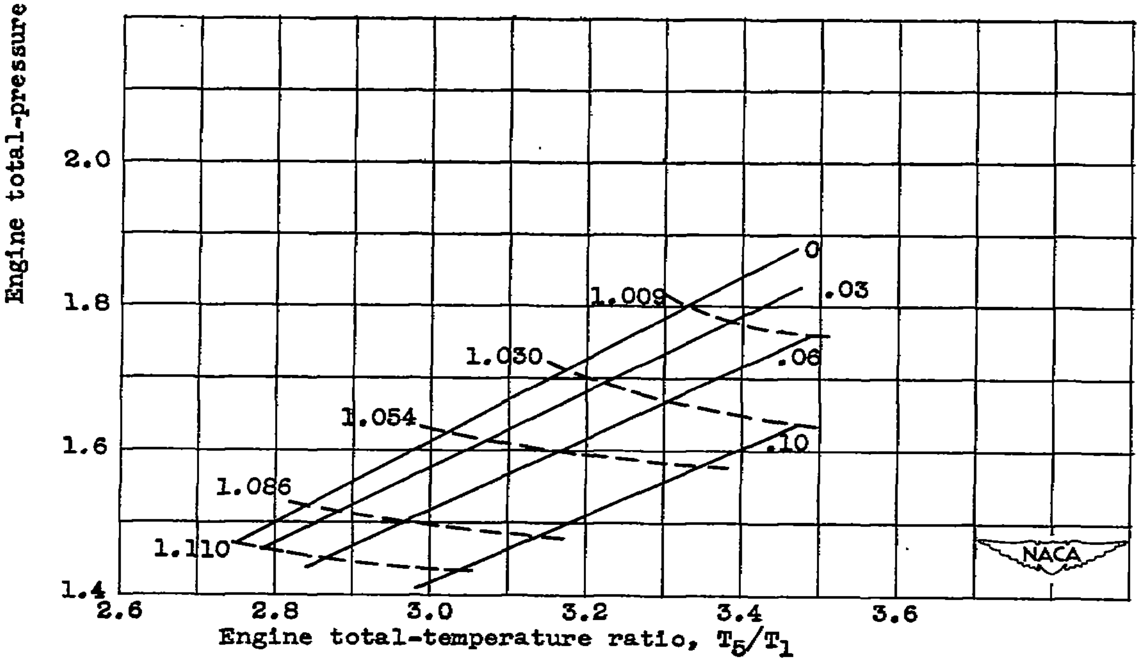
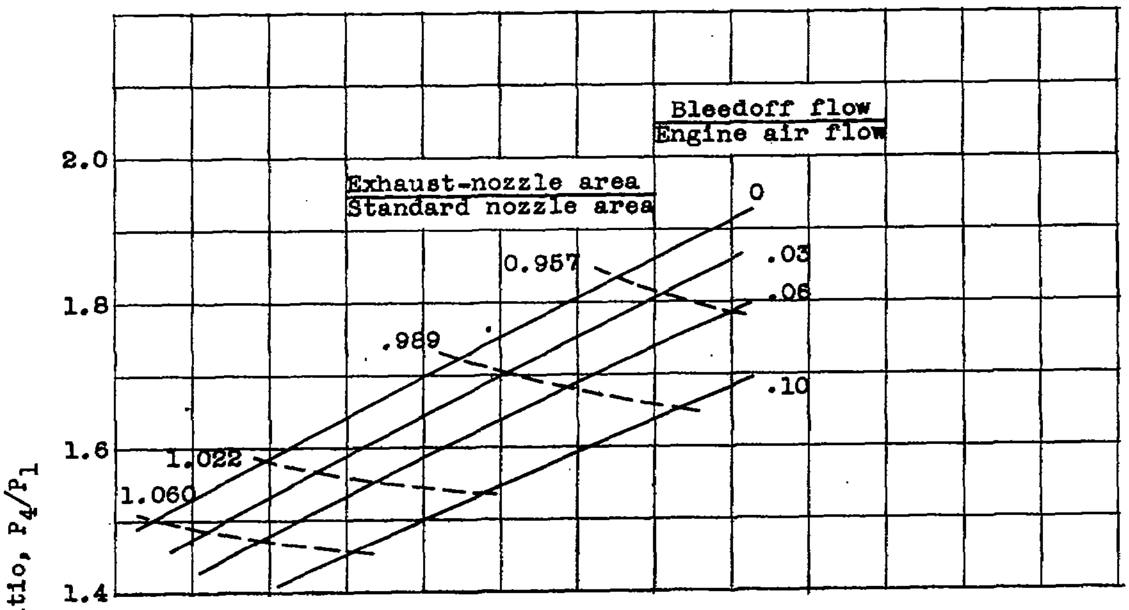


(a) Engine speed, 0.885 rated; altitude, 25,000 feet.

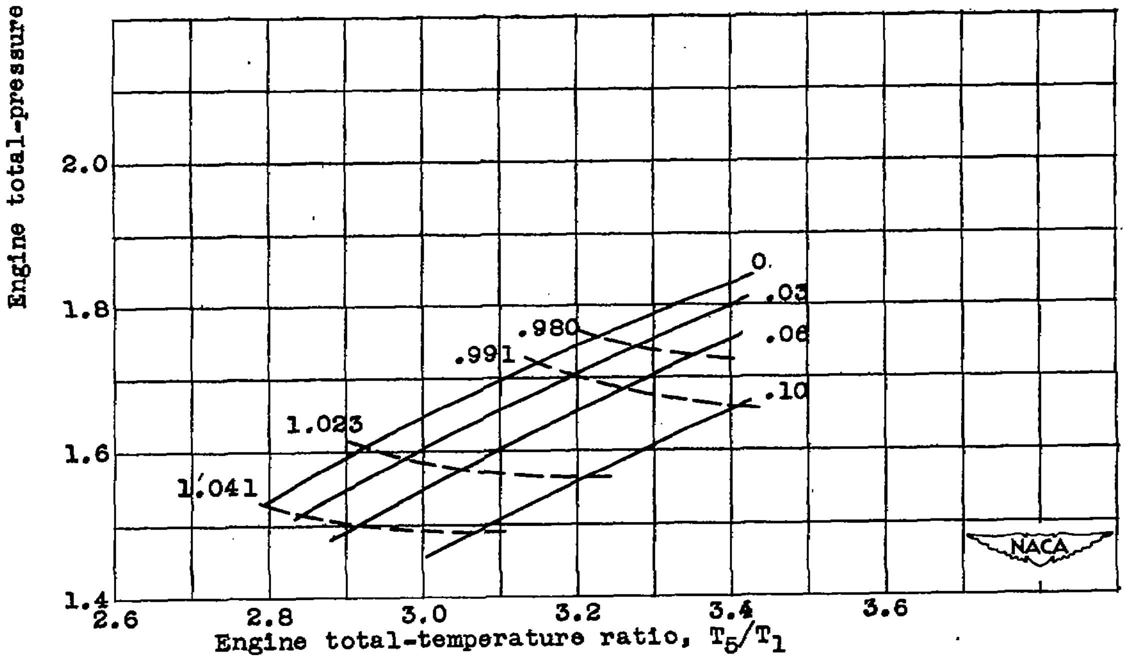


(b) Rated engine speed; altitude, 25,000 feet.

Figure 8. - Effect of compressor-outlet bleedoff on engine pumping characteristics. Flight Mach number, 0.53.

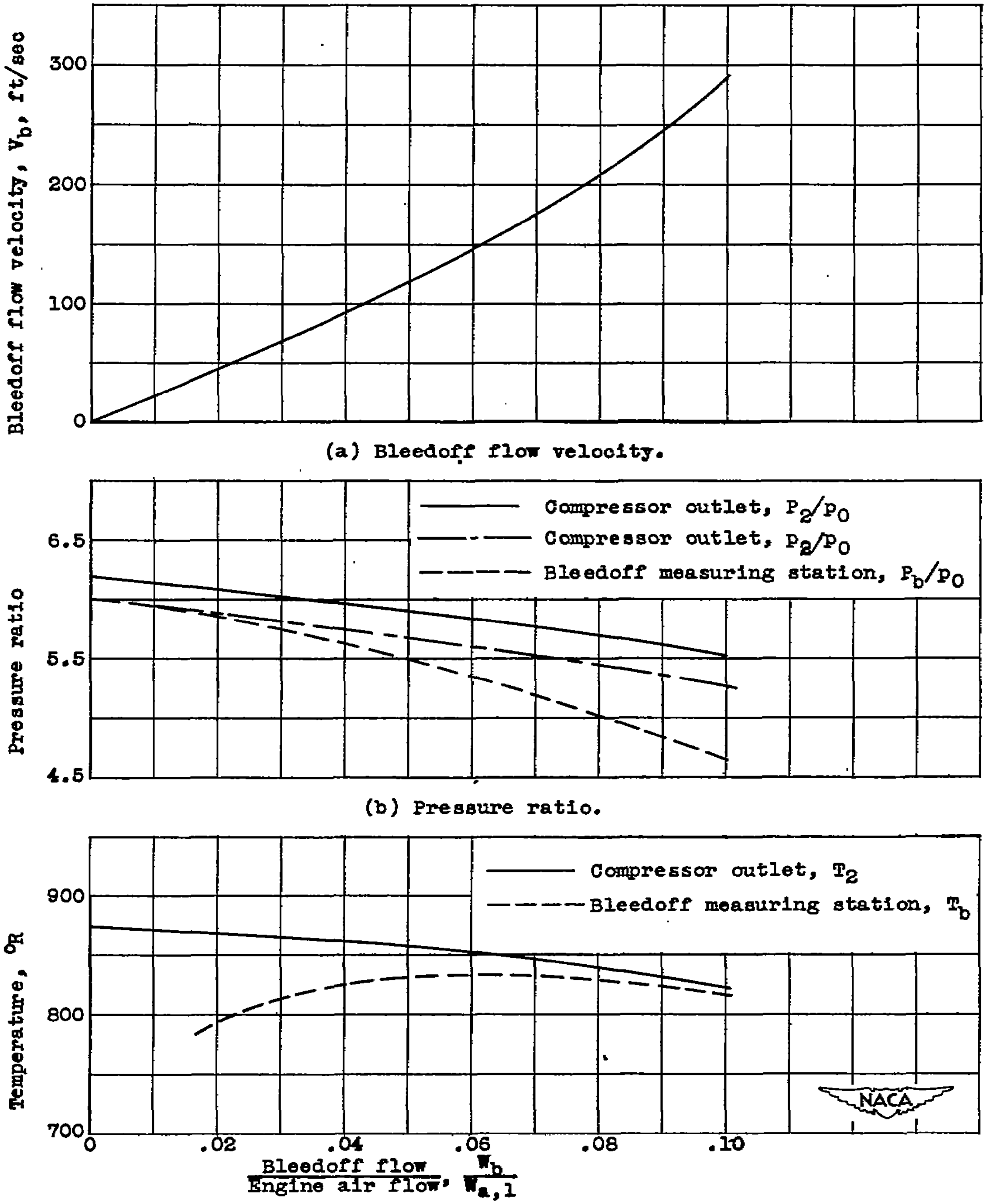


(c) Engine speed, 0.93 rated; altitude, 25,000 feet.



(d) Engine speed, 0.93 rated; altitude, 40,000 feet.

Figure 8. - Concluded. Effect of compressor-outlet bleedoff on engine pumping characteristics. Flight Mach number, 0.53.



(c) Total temperature.

Figure 9. - Variation of conditions at compressor outlet and bleedoff-flow measuring station with bleedoff flow for operation at maximum thrust. Altitude, 25,000 feet; flight Mach number, 0.53; standard exhaust-nozzle area; turbine-outlet temperature, 1665° R.